The NA61/SHINE long target pilot analysis for T2K

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Abstract. The NA61/SHINE collaboration performed measurements of pC interactions at 31 GeV/c beam momentum with a full size replica of the T2K target (1.9 interaction length) during a pilot run in 2007. Larger statistics runs were also conducted in 2009 and 2010. The NA61/SHINE setup consists in a large acceptance spectrometer located on the H2 beamline of the SPS at CERN. For the first time, the kinematical phase space of interest for an accelerator based neutrino experiment (i.e. kinematical phase space of pions/kaons exiting the target and producing neutrinos in the direction of the near and far detectors) is fully covered by a single hadron production experiment. In a first stage, yields of positively charged pions were measured at the surface of the target. The analysis of the 2007 data set presented here demonstrates that **a)** high quality long target data were successfully taken with the NA61/SHINE apparatus, and **b)** for the first time, the T2K neutrino flux predictions can effectively be re-weighted with the NA61/SHINE long target data.

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1. Motivations for long target measurements for T2K

A prediction of the neutrino beam content at the T2K ([1], [2]) far detector is given in Table 1. The ν_μ flux is predominantly ($\sim$ 95%) produced by the decay in flight of positively charged pions focused by the magnetic horns of the beamline. While $\sim$ 30% of the ν_e flux is produced from the decay of positively charged kaons, $\sim$ 50% of it is due to muons produced in the decay of the same charged pions that generate the ν_μ flux. Thus, in a first stage, pion production data will constrain both ν_μ and ν_e fluxes.

Table 1. Composition of the neutrino beam and its various species at the far detector. Integrated values are quoted. Predictions obtained with the GCALOR model and horn currents set to 320 kA each (T2K was running with horn currents of 250 kA in 2010/11).

ν	Flux		Source									
			π^+ or π^-		K$^+$ or K$^-$ (K2)		K$^+$ or K$^-$ (K3)		K^0_L		μ^+ or μ^-	
species	Abund.	$\langle E_\nu \rangle$	%	$\langle E_\nu \rangle$	%	$\langle E_\nu \rangle$	%	$\langle E_\nu \rangle$	%	$\langle E_\nu \rangle$	%	$\langle E_\nu \rangle$
ν_μ	1.0	0.79	95.1	0.64	4.5	4.0	0.24	1.93	0.1	2.05	0.01	0.75
$\bar{\nu}_\mu$	0.0701	1.14	85.8	1.05	4.6	3.1	0.2	1.56	1.3	2.05	8.0	0.68
ν_e	0.0110	1.40	1.0	1.48	–	–	33.0	2.25	12.5	2.38	53.3	0.64
$\bar{\nu}_e$	0.0017	2.18	0.4	2.32	–	–	14.7	1.84	77.6	2.38	7.2	0.75

In terms of hadron production measurements, the pion contribution to the ν_μ flux at the far detector can be decomposed into a *direct* component and a *target* component. The

first contribution originates from pions directly produced in the proton primary interaction (secondary pions) or in the decay of a secondary particle. The *target* contribution refers to all pions exiting the target or pions produced in the decay of an outgoing particle. The dependence of these contributions on the neutrino energy is depicted in Fig. 1 (left and middle panels). While the direct component contributes to $\sim$ 60% of the ν_μ flux at the beam peak energy of $\sim$ 600 MeV, the target component contributes to $\sim$ 90% of the flux. Thus, thin target measurements ($p + C \rightarrow \pi^+ + X$ at 30 GeV) for T2K constrain up to 60% of the ν_μ flux prediction at the far detector, the remaining 40% being produced in secondary interactions in the target and elements of the beamline. Long target measurements would constrain up to 90% of the flux prediction. In this case, only 10% of the flux due to secondary interactions out of the target would require constraints from other data.

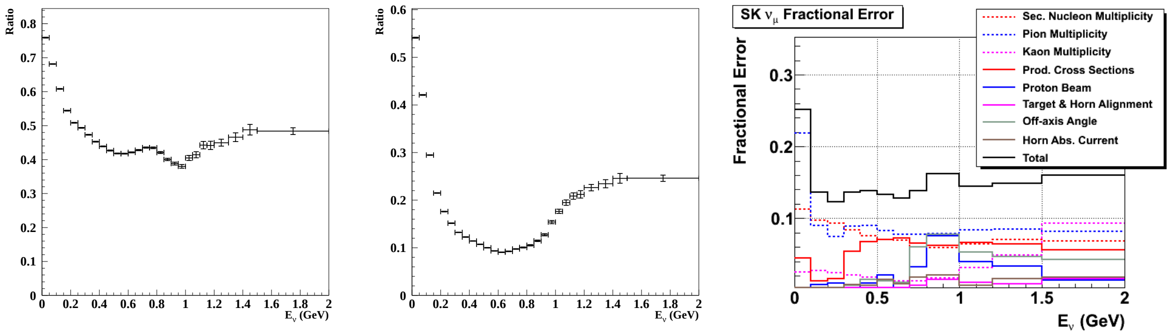

Figure 1. Ratio of (1-direct) [left] and (1-target) [middle] to total contribution for the ν_μ flux at the far detector. Current error envelopes for the ν_μ flux at the far detector [right] (for the analysis described in [4]).

As depicted in Fig. 1 (right panel), the total fractional error on the T2K ν_μ flux prediction ([3], [4]) at the far detector is $\sim$ 15% at the beam peak energy. Uncertainties arise from two main contributions: uncertainties related to the beamline setting (e.g. beam optics, beam direction, alignment and currents of the focusing horns) and those related to the re-weighting procedure based on the NA61/SHINE thin target data (within 5 to 10 %)[5]. The fractional error at the beam peak energy is dominated by uncertainties from the second contribution (i.e. pion/kaon multiplicity, secondary nucleon multiplicity and production cross sections). In particular, uncertainties on the re-weighting of secondary nucleon and production cross sections for secondary interactions are applied to $\sim$ 40% ($\sim$ 10%) of the flux in the case of the thin (long) target based re-weighting. These uncertainties rely on interpolation between sparse data sets or comparison to models and are often poorly known. In the case where flux predictions are re-weighted by long target data, these contributions are taken into account at once and there is no need for error prone estimates of secondary interactions in the target. Long target data are therefore needed to obtain a precision of 5% or better on the absolute flux prediction.

2. The NA61/SHINE long target measurements for T2K

The 2007 NA61/SHINE pilot data were taken with a replica of the T2K target at 30 GeV beam energy. The NA61/SHINE spectrometer consists in a set of 5 time projection chambers (TPCs) complemented by an array of time-of-flight (ToF) detectors located downstream of the TPCs, allowing for a full coverage of the forward pion production of interest for T2K (i.e. phase space of pions exiting the target and producing neutrinos in the direction of the near and far detectors). Details of the experimental setup are given elsewhere [5]. The trajectory of each beam proton track is reconstructed with a set of beam position detectors that allow to determine the position of the beam impact on the upstream face of the target. The usage of the ToF in the analysis

assures that selected tracks in the TPCs originate from single proton interactions in the target. Data can therefore be normalized to the total number of protons on target (POT).

Tracks reconstructed in the TPCs are extrapolated back through the magnetic field from their first measured point to the surface of the target. A point-of-closest-approach is found between the trajectory of the track and the surface of the target. This requires a precise knowledge of the relative alignment of the beam and target, which is determined by using both beam and TPC tracks. For the 2007 pilot run, the target was tilted with respect to the beam axis in both horizontal (~ 5 mrad) and vertical (~ 2.8 mrad) directions. The misalignment was taken into account in the extrapolation procedure and effects on the outgoing pion yields (additional systematic uncertainty) studied with dedicated Monte-Carlo simulations. The target is split into 5 bins of 18 cm each along the beam (z axis), and a last bin corresponding to the dowstream face of the target that covers the very forward (below 40 mrad) pion production. Analysis cuts are optimized to improve the momentum and polar angle resolutions at the first measured point on track that determine the achievable resolutions on target, estimated to $\sigma_z = 5$ cm, $\sigma_p/p = 3\%$ and $\sigma_\theta/\theta = 6\%$ for the longitudinal, momentum and polar angle resolutions respectively. As depicted in Fig. 2 (left panel), tracks can effectively be reconstructed on the surface of the target. The analysis coverage extends up to 20 GeV/c in the forward production region (< 40 mrad) and covers angles up to 280 mrad at lower momentum.

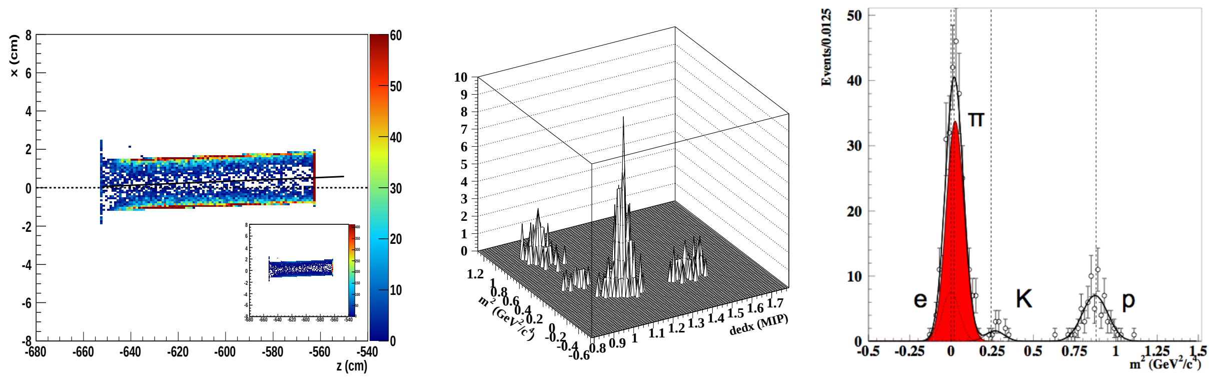

Figure 2. Distribution of the point-of-closest-approach on target in the x-z projection [left], data distribution in the $\{ToF, dE/dx\}$ phase space for $40 < \theta < 100$ mrad and $2.4 < p < 3.2$ GeV/c [middle], and projection of the fit result along the ToF axis [right].

The particle identification (PID) relies on the energy loss (dE/dx) measurement in the TPCs and the time-of-flight that is used to compute the particle mass squared. The combination of the two signals provides a powerful PID over a large momentum range. Yields of positively charged pions exiting the target are extracted in bins of (p, θ, z) using a 2d-likelihood minimization (see Fig. 2, middle and right panels). Fig. 3 shows that such yields can effectively be measured at the surface of the target.

The FLUKA simulation package [7] used in the T2K beam simulation was interfaced to the NA61/SHINE simulation chain for which a PID based on data parametrizations was furthermore implemented. Data and Monte-Carlo are processed identically with the same reconstruction chain and PID analysis. Thus, reconstructed yields of positively charged pions can be compared to reconstructed Monte-Carlo predictions prior to any corrections necessary to get absolute yields (e.g. all Monte-Carlo based corrections such as acceptance and decay corrections, reconstruction efficiency, etc). Such a comparison is depicted in Fig. 3 (top left panel) with the corresponding re-weighting factors (top right panel), defined as the ratio of data to Monte-Carlo yields. Current uncertainties on the re-weighting factors are dominated by the statistical uncertainty which is typically 10% due to the very poor statistics of the 2007 pilot data. Systematic uncertainties are

within 5-10%, the dominant source being PID (1-5%), followed by target misalignment (3%) and normalization (1.4%). Systematics from ToF efficiency, beam momentum and target density are all below 3%.

Comparisons of FLUKA-standalone predictions for the T2K beam simulation to the NA61/SHINE long target data are also shown as an example in Fig. 3 (bottom panel), for predictions re-weighted with the NA61/SHINE thin target and long target data. More details on the NA61/SHINE long target data analysis and re-weighting procedure are given in [6].

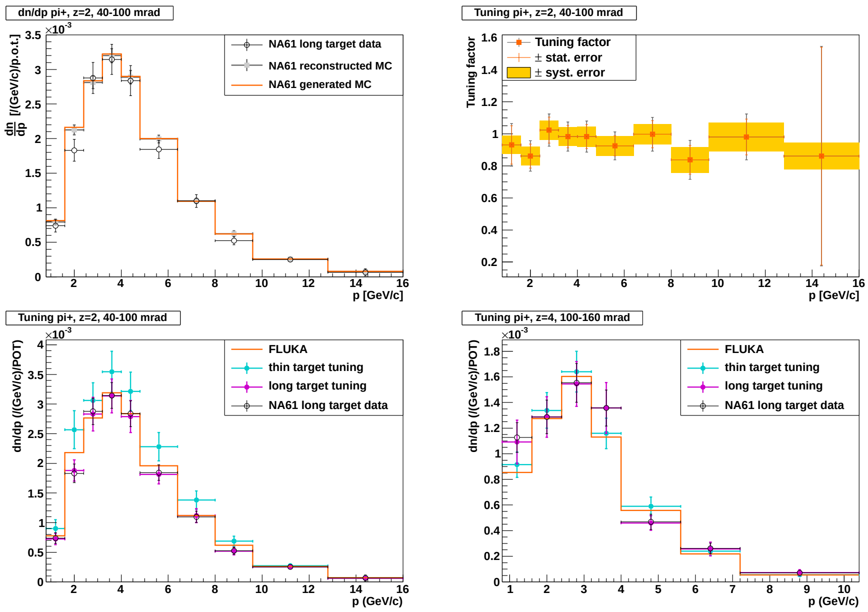

Figure 3. Data and Monte-Carlo yields of positively charged pions normalized to the bin size and to the number of protons on target over the second longitudinal bin of the target for $40 < \theta < 100$ mrad [top left], and corresponding re-weighting factors [top right]. Comparisons of nominal FLUKA-standalone predictions with thin target and long target re-weighting to the NA61/SHINE long target data for different angular intervals [bottom panel].

Statistical uncertainties will be reduced with the 2009/2010 long target data sets, and further improvements are expected (in particular for the target alignment) to reduce the systematic uncertainties down to 5% or better. The pilot analysis of the 2007 NA61/SHINE long target data demonstrates that the T2K neutrino flux predictions can effectively be re-weighted with long target data. A first preliminary re-weighting of the ν_μ flux prediction at the far detector was already implemented and compared to the prediction based on the 2007 NA61/SHINE thin target data ([5], [6]).

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